Contribution of ambient vibration recordings (Free-field and buildings) for post-seismic analysis: the case of the Mw 7.3 MARTINIQUE (French lesser ANTILLES) earthquake, november 29, 2007

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CONTRIBUTION OF AMBIENT VIBRATION RECORDINGS (FREE-FIELD AND BUILDINGS) FOR POST-SEISMIC ANALYSIS: THE CASE OF THE MW 7.3 MARTINIQUE (FRENCH LESSER ANTILLES) EARTHQUAKE, NOVEMBER 29, 2007

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ABSTRACT

Following the Mw 7.3 Martinique earthquake, November 29th, 2007, a post-seismic survey was conducted by the Bureau Central Sismologique Français (BCSF) for macroseismic intensities assessment. In addition to the inventories, ambient vibration recordings were performed close to the particularly damaged zones in the free-field and the buildings. The objective of the paper is to show the relevancy of performing ambient vibration recordings for post-earthquake surveys. The analyses of the recordings aim at explaining the variability of the damages through site effects, structure vulnerability or resonance phenomena and to help the characterization of the post-seismic building integrity. In three sites prone to site effects, we suspect damage to be related to a concordance between soil fundamental frequency and building resonance frequency. Besides, the recordings of ambient vibrations at La Trinité hospital before and after the earthquake allow us to quantify the damage due to earthquake in terms of stiffness loss.

HIGHLIGHTS:

- We performed ambient vibration recordings in both soil and structure after a damaging earthquake
- We investigate the sources of damage to buildings
- We compare pre-and post earthquake recordings to evaluate damage grade
- We propose recommendations for the use of such recordings in post seismic survey.

KEYWORDS: Ambient vibrations, site effect, resonance, post-earthquake survey, damage, Martinique earthquake.

INTRODUCTION

A large part of knowledge in the fields of earthquake engineering and engineering seismology has been accumulated during post-seismic surveys all around the world. These surveys have many different objectives: (1) estimate the buildings safety right after the earthquake, (2) characterize the ground motion by establishing macroseismic maps, (3) provide feedback for earthquake engineering by studying damage features and, eventually (4) help urban planning in defining zones with ground motion amplification and induced effects (liquefaction, landslides…). However, the knowledge of the structural damage causes is prior information necessary to relevantly reach these objectives. For a given deformation capacity, e.g. associated to a building class, damage will only depend on the building response to the ground motion. The building response depends on the incident seismic motion (that can be largely affected by the site response) and its representing parameters (maximal amplitude, frequency content…) with regard to the structure and its dynamic properties (e.g. Clough & Penzien, 1993). Thus, two key parameters among those influencing the seismic demand can be considered: 1) the resonance frequencies of the site and 2) the building resonance frequencies.

Seismic noise recordings in free-field and ambient vibration recordings in buildings are robust and low cost methods for estimating the soil and structure low-strain resonance frequencies. Since the 1990s and the widespread studies for site effects based upon the Horizontal to Vertical Noise Spectral Ratio (HVNSR), several papers have shown the relevancy of HVSNR to partially explain damage locations and/or grades (e.g., Anderson et al., 1986; Guéguen et al, 1998; Duval et al, 2006; Theodoulidis, 2008). However, other studies show that HVNSR alone cannot be directly linked to damage distribution (Mucciarelli et al, 1998, 1999; Trifunac et al, 2000; Tertulliani, A. et al., 2012) and the damage variability can also be related to the building capacity rather than the site characteristics (Chatelain and Guillier, 2008).

Besides, ambient vibration recordings in buildings have gained more and more interest for last decades, for earthquake engineering and civil engineering applications. The elastic fundamental frequency is a key-parameter in earthquake engineering for building response assessment (e.g. Michel et al., 2010a, 2010b) and structural health monitoring (e.g. Carden and Fanning, 2004, Dunand et al., 2004).

The joint approach (i.e. free-field and building investigation) can be relevant for post-seismic evaluation of the origin of the damage variability and building integrity. Gallipoli et al (2004), Gosar et al. (2009) and Mucciarelli et al. (1999, 2010) showed by ambient vibrations applications that soil-structure resonance could play a major role in damage location.

Following the 29th November 2007 Mw=7.3 Martinique earthquake, a post-seismic survey was set up to collect macroseismic data by the Bureau Central Sismologique Français in charge of the definition of the macroseismic intensities after earthquakes (Schlupp et al., 2008). During this survey, the authors performed ambient vibration recordings in highly damaged zones.

The scope of this paper is to show a case study of the usefulness of the joint utilisation of ambient vibration recordings in free-field and building to (1) improve the evaluation of the damages, (2) understand the origins of the damage variability by understanding the low-strain response of the soil and building and (3) show the relevancy of these information to complete a macroseismic study such as the one led by the BCSF.

DESCRIPTION OF THE CASE STUDY

The 29th November 2007 Martinique earthquake occurred at rather great depth (152 km) with a moment magnitude of 7.3 (Guéguen, 2012) located in the northwest at 30 km of the island. The French Accelerometric network (RAP http://www-rap.obs.ujf-grenoble.fr, Pequegnat et al., 2008) recorded ground motions due to the main shock in 34 stations in Martinique (Fig. 1). The horizontal Peak Ground Accelerations (PGA) is ranging from 0.3 to 4 $m.s^{-2}$ through the island. The local variability is large, e.g. in Fort-de-France from 0.4 to 2 $m.s^{-2}$ over several hundreds meters, indicating the importance of local soil conditions. Macroseismic intensities using EMS98 (Grünthal et al., 1998) on the island were estimated between V and VI-VII (Fig. 1). We performed ambient vibration recordings in free-field and in buildings in three sites (Fig. 1), selected for the high level of structural damages compared to the macroseismic intensities estimated in the town.

Figure 1

Site 1. In Le Francois, damage due to the earthquake did not exceed grade 2 (EMS98) except for two school buildings, which suffered damage up to grade 3. The building A of Anne Marc school (Fig. 2) is a two-storey building with reinforced concrete (RC) frames built in 1973 without earthquake-resistant design on ancient mangrove, sedimentary deposit prone to site effects (Guéguen et al., 2011). It exhibits a low lateral stiffness in the longitudinal direction and a soft story at the ground floor. After the earthquake, we observed cracks at the bottom of several columns of the ground floor as well as numbers of cracks in partition walls and falls of mortar (damage grade 3 EMS98).

Site 2. In La Trinité, the AFPA buildings (E and H) were strongly damaged. Both structures, built in the 1970s without earthquake-resistant design, were studied but this paper focuses on building E. It is a two-storey building with RC frames and a soft ground floor (Fig. 2). This building is divided by thin filled joints into 4 L-shaped blocks, sensitive to torsion due to the eccentricity of the rigidities. Moreover, infill brick walls are not symmetrically distributed. It suffered slight structural damage (small cracks in columns at the ground floor) and moderate non-structural damage (large cracks in partition walls). According to soil studies during the construction, these buildings are founded on sedimentary deposits.

Site 3. The hospital of La Trinité is a RC infilled frames structure built in 1974. Excluding low-rise aisles, three high-rise blocks (called A, B and C) are respectively 9, 8 and 7 stories above the ground level and separated by 5 cm joints filled by Styrofoam (Fig. 2). After the earthquake, small cracks appeared in the structural system, larger cracks and plaster falls in the infill walls and false ceiling pieces fell down, associated to moderate damage (grade 2).

Figure 2

EXPERIMENTS, PROCESSING AND RESULTS

Ambient vibration recordings in free field and in structures were at least 15 min. long with seismometers (Lennartz 3D 5s and LITE) and a 24-bits Cityshark digitizer (Chatelain et al., 2000) at a sampling frequency of 150 Hz to 200 Hz. The N component of sensors, were oriented in one of the main direction of the studied building. The free-field recordings were analyzed using Horizontal to Vertical Noise Spectral Ratio (HVNSR) method where the Fourier Transforms of at least 30 s windows selected with an anti-triggering STA/LTA (Short Term Averaging, Long Term Averaging) algorithm are averaged and smoothed following Konno and Ohmachi (1998) procedure (b=40). The HVNSR is given by the ratio of the quadratic mean of the horizontal spectra by the vertical one and interpreted following the SESAME project recommendations (Bard, 2004). If the SESAME criteria are fulfilled, the frequency of the peak is likely to be related to the fundamental frequency of the site.

Depending on the importance of the building, on the complexity of the structure and on the severity of the damages, one must adapt the experimental procedure. Ambient vibrations in buildings were recorded with one or two sensors simultaneously. Several processing techniques were used depending on the number and position of the recording points. For single station recordings at the building top, the Power Spectral Density (PSD) spectra have been estimated (square of the Fourier Transform amplitude) using the same procedure as for the ground without smoothing. Interpretation of these spectra in terms of building dynamic properties may be ambiguous and were done with caution. For simultaneous recordings at different points, the Frequency Domain Decomposition (FDD, Brincker, 2001) is used as in Michel et al. (2010a). Peaks in the first singular values can be interpreted as resonance frequencies and singular vectors as modal shapes. The knowledge of modal shapes is crucial for the interpretation of structural modes, but their quality depends on the number and position of recording points.

For both ground and structure, the resonance frequencies obtained from ambient vibration recordings are valid for low strains. During strong motion, nonlinear response of the soil (e.g. Régnier et al., 2012), the building (e.g. Michel and Guéguen, 2010) and the soil–structure interaction can temporarily make the observed natural frequencies shifting to lower frequencies. Nonetheless, Puglia et al. (2011) showed that the frequencies variations due to nonlinear soil behavior were not relevant (during the l'Aquila earthquake for which acceleration up to 0.7 g were recorded) from building design standpoint. In this article, we study the link between damage and the similarity in the natural linear frequencies of the soil and the structure.

In the Anne Marc School (site 1), both soil and structure recordings were performed to evaluate and compare the soil and structure responses. The analysis of the recordings (Fig. 3) shows that the peak frequency of the HVNSR in free field (1.75 Hz) and the first peaks of the PSD in the structure in both directions (1.6 and 1.8 Hz in the longitudinal and transverse directions, respectively) are very close. It indicates that the structure is sensitive at low strain to the 1D resonance frequency of the soil and, thus, that a resonance between soil and structure eventually occurred during the Martinique earthquake, inducing higher damage.

Figure 3

In the AFPA building (site 2), the same procedure was followed but with more recording points. Free-field recordings were performed at different ground levels (S1, 3 m from the building at the same level, S2, 15 m from the building downhill, Fig. 2). Frequency peaks are clearly observed at 2.4 and 2.8 Hz in the HVNSR for S1 and S2, respectively (Fig. 4), the difference of the frequencies being certainly due to the variation of the deposit thickness.

In three of the 4 L-shaped blocks of the building (named L1, L2 and L3), we recorded ambient vibrations simultaneously at the ground floor, the first and the second stories. The chosen sensor placement, however, did not allow to fully understand the dynamic behaviour of the building. The fundamental modes appear between 2.7 and 4.3 Hz and include bending and torsion. These modes are quite close to the fundamental frequency of the ground found previously (2.4 to 2.8 Hz). However, the other AFPA building (building H), not detailed here, has higher resonance frequencies (3.5 to 4.5 Hz) and was therefore less prone to resonate with the ground but was more damaged than building E (damage grade 3) also with typical damage due to torsion. In this case, the design of the structure (lack of symmetry in the load bearing system) was therefore probably the main cause of damage during the earthquake.

Figure 4

Finally, in the hospital building (site 3), full-scale ambient vibration recordings have been performed several months before the event. After the Martinique earthquake, we recorded ambient vibrations in the building to analyse the evolution of its dynamic behaviour related to damage.
As illustrated in Fig.5, the soil at his site is prone to site effect with a clear peak at 2.4 Hz. The Fourier transform of the recordings at the top of the block A shows that the building resonance frequencies are close to the HVNSR peak around 2.5 Hz.

Figure 5

Data recorded in 93 points of the structure before the earthquake has been reprocessed using FDD technique (Brincker et al., 2001) (Fig. 6). In this dataset, two close clear peaks carried by the 2 first singular values indicate the presence of 2 modes around 2.5 Hz. The first mode at 2.45±0.03 Hz is the first longitudinal bending mode of the whole building (Fig. 6). The second mode at 2.56±0.03 Hz is the first transverse bending mode of the structure. The modal shape indicates that these modes are partly coupled to torsion but with differences for each block. The amplitudes of the higher modes are lower and are not detailed here.

Figure 6

The PSD of the ambient vibration recordings in the structure at the same position before and after the earthquake have been calculated (Fig. 7). Assuming only a moderate frequency decrease, the knowledge of the pre-earthquake structural behaviour allows interpreting the peaks of the post-earthquake recordings. The first longitudinal mode has shifted from 2.45±0.03 Hz to 2.00±0.05 Hz, i.e. 18±4% frequency drop. Moreover, the first transverse mode has shifted from 2.56±0.03 Hz to 2.15±0.05 Hz, i.e. 16±4% frequency drop. Dunand et al. (2004) already used this technique at a larger scale after the Mw=6.8 Boumerdes, Algeria earthquake (May 21, 2003) and suggests a value of 40% frequency drop as a limit for the building to be impossible to retrofit (difference between orange and red classification). The observed damage is therefore noticeable but not critical as denoted by the assigned damage grade 2 EMS. However, such comparisons are still lacking in the literature to propose a relationship between frequency drop and damage grade.
Ambient vibration recordings in free field were as well performed before and after the earthquake. The soil fundamental frequency at 2.4 Hz is found to be the same. The resonance of the building before the earthquake (2.45 Hz for the first mode) is very close from the soil fundamental frequency. Resonance between the soil and the building response increased the seismic demand of the structure, which explains most probably the damage.

Figure 7

CONCLUSIONS

Through these examples, we illustrated how to use ambient vibration recordings in soil and structure in post seismic survey. This approach helps to understand the possible causes of damaged zones distribution. Moreover, ambient vibrations recordings are low cost and can be rapidly set up after an earthquake.

With soil recordings, we investigated the possibility of soil to be prone to site effect. Link with damage is however not straightforward: site effect only increases the seismic demand around the soil resonance frequency. However, using both soil and structure recordings, the sensitivity of the structure to the 1D linear soil resonance can be checked. Thus, conclusions can be made on the possibility of having a resonance between soil and structure, which increases the seismic demand in the building and can induce higher damage.

In the three study-sites, the free field ambient vibration recordings indicate the occurrence of site effects. We found similarities between soil and structures resonance frequencies. It appears that resonance played a role in damage distribution.

In the La Trinité hospital, the fundamental frequency suffered a shift of 15-20% during the earthquake. Besides, the permanent frequency shift was related to a loss of stiffness of the structure that can be associated to a damage grade 2 EMS 98. To analyse temporary frequency shift, structure permanent monitoring is necessary.

According to this case study, we can make some recommendations for the use of these recordings in post seismic survey. These recommendations should be adapted to the building importance, damage level and the objectives of the recordings. In our experience, such post-seismic survey should be focused on important buildings (importance class III and IV in Eurocode 8).

- Objective 1: Looking at potential concordance between soil and structure frequencies. In this case only one recording at the top of the structure and one on the free field (in the same geological context as the soil under the structure) are sufficient. Such measurements are interesting to understand the sources of damage. Analysis of such measurements could be used as one support (among others) to make decision on whether the building should be retrofitted (so as the resonance frequency of the building is different from the soil one).

- Objective 2: Having the modal shape associated to the predominant frequency. It requires simultaneous recordings at different storeys of the building. Such information could be very useful to constrain the numerical simulation of the dynamic behaviour of the structure and to test retrofitted solutions. Besides it can also be used to evaluate the evolution of the damaged structure behaviour during the aftershock sequences.

- Objective 3: Evaluate the stiffness loss of the structure and evaluate damage grade. It requires recordings at the top of the building before and after the earthquake. It is very useful in crisis management and is a support to emergency diagnosis of the building and visual screening of damages state. It is a quantitative measurement that is complementary to expert advises. Such measurements should be performed for high stake buildings of class IV in Eurocode 8.

For risk mitigation and to anticipate post earthquake crisis management, recordings of ambient vibrations should be performed in structures of high importance. Although permanent monitoring has a heavy cost, it should be considered for a small number of typical buildings.

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FIGURES

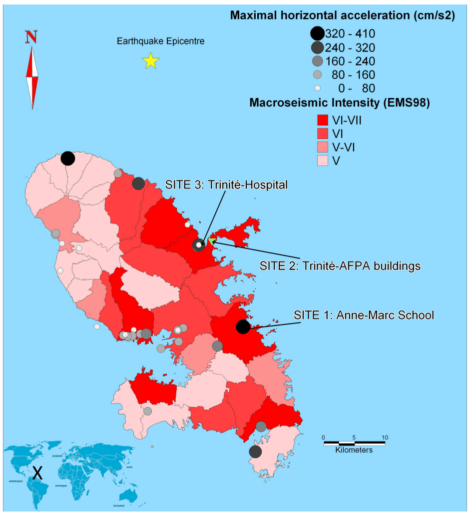
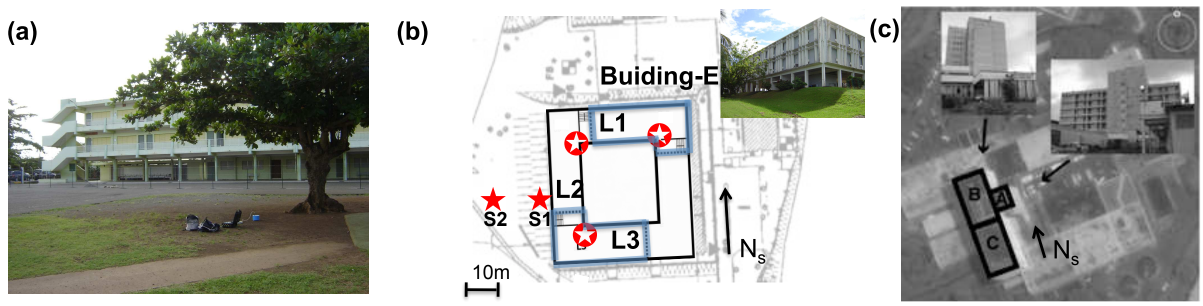


Figure 1 Map of the macro seismic intensity at the Martinique island after the 28th November 2007 earthquake. The circles indicate the position of the RAP stations that recorded the earthquake (size scale is function of the maximal PGA on the three components in cm/s^2), and location of the sites that were studied.



Anne-Marc School (St François) **AFPA Building (Trinité)** **Hospital (Trinité)**

Figure 2: (a) Site 1- Location of the recordings performed at the Anne-Marc school in Le François. The building ambient vibration recording is performed at the second floor half length. (b) Site 2- AFPA Bulding E at the Trinité district. (c) Site 3 - The La Trinité Hospital site (aerial view) with study-blocks A, B and C. The Sensors were oriented in the transverse direction of the buildings (the N component of the sensors is called Ns)

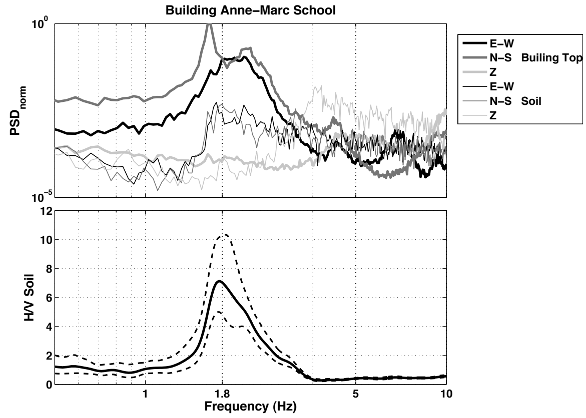


Figure 3: Site 1 – Top: Normalized Power Spectral Density of the recordings in the structure (solid lines) and the recordings in the soil (dashed lines) in the 3 directions East (E) North (N) and Vertical (Z). Bottom: HVNSR of the free field recording (mean, 16 and 84 percentiles).

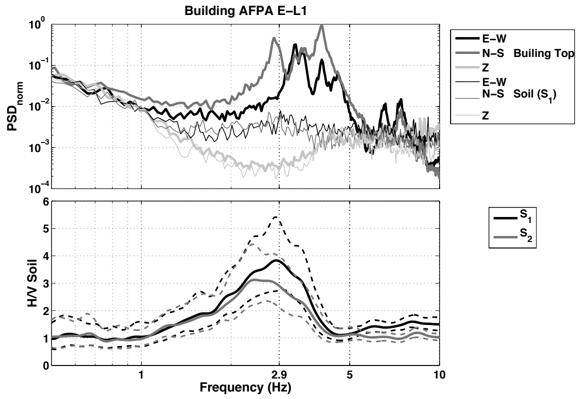


Figure 4: Site 2 - Top: Normalized Power Spectral Density of the recordings in the structure (solid lines) and the recordings in the soil (dashed lines) in the 3 directions East (E) North (N) and Vertical (Z). Bottom: HVNSR of the free field recording (mean, 16 and 84 percentiles).

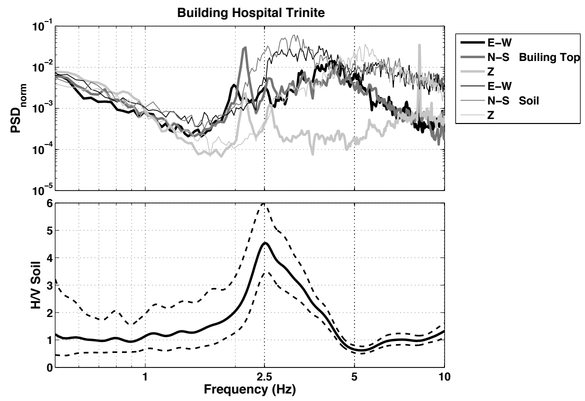


Figure 5: Site 3 - Top: Normalized Power Spectral Density of the recordings in the structure (solid lines) and the recordings in the soil (dashed lines) in the 3 directions East (E) North (N) and Vertical (Z) of the recording at the top of the block A. Bottom: HVNSR of the free field recording the mean, 16 and 84 percentiles.

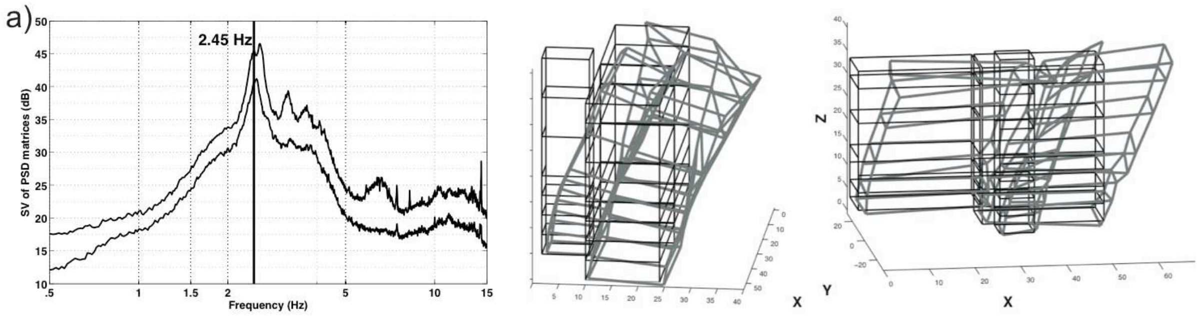


Figure 6: Site 3 - Pre-earthquake modal analysis results. a) FDD spectrum, b) Modal shapes of the first transverse and longitudinal modes at 2.56 and 2.45 Hz, respectively.

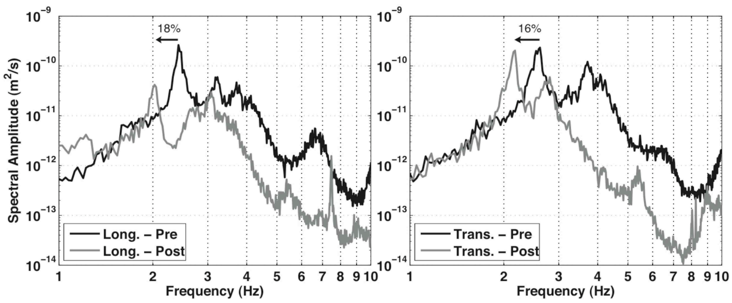


Figure 7: Site 3 – Pre- and post-earthquake PSD spectra in block A in the longitudinal (left) and transverse (right) directions.